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6. AUTHOR(S)

Emmett N. Leith

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Michigan
Dept. of EECS
1301 Beal Avenue, Room 1108 EECS Bldg.
Ann Arbor, MI 48109-2122

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13. ABSTRACT (Maximum 200 words)

A theoretical investigation was made into the angular correlation that exists between two plane waves propagating through a scattering medium. Comparisons were made with the coherence existing between the angular correlation and the correlation of the exiting waves with a reference wave. Such studies are important to understanding how a wave-field can be recovered after propagation through a scattering medium. A new concept, that of spatial filtering time gating, was investigated. This idea enables propagation through scattering media to be studied in a simple way, unencumbered by the complexities of short coherence length interference. New concepts in confocal imaging were explored, relating this process to volume holography and to synthetic aperture imaging. Confocal imaging theory was reformulated in the broadest possible way, giving rise to a basic theory of confocal imaging that encompasses all confocal imaging processes, in their many diverse forms, including the novel forms developed here. A new method of recording scattered light was developed. This method is based on up-conversion in non-linear crystals and records only the light component in which the propagation vector is aligned along some preferred axis. This method will further improve the capability for imaging of objects embedded in scattering media. Phase conjugation methods were employed in a novel way to detect objects embedded in scattering media

14. SUBJECT TERMS

Spatial coherence, scattering media, confocal imaging

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Sincerely,

Emmett N. Leith
University of Michigan
1301 Beal Avenue
1108 EECS Bldg
Ann Arbor, MI 48109-2122

FINAL REPORT

Proposal Number: P-35056-PH, P36938-PH-AAS

Period Covered: 7/1/96 – 12/31/00

Title: Investigator of Coherence Imaging, Photon Migration, and Short-Pulse Image Processing

Contract Number: DAAH04-96-1-0254, DAAG55-97-1-0243

University of Michigan
Department of Electrical Engineering and Computer Science
1108 EECS Bldg.
Ann Arbor, MI 48109-2122

Emmett N. Leith

A. Statement of problem studies the proposal research involves 3 related areas:
   (a) Coherence imaging, in which the coherence effects of the light either result in the formation of an image or contributes significantly to the imaging process,
   (b) Photon migration, which is concerned primarily with image formation through highly scattering media, and
   (c) Image processing with femtosecond pulses of light, in which the special properties of extremely short pulses significantly influence image-processing techniques.

B. Summary of the most important results:

1. We extended our development of ensemble averaged imaging. We measured both the ensemble-averaged phase, as well as, the ensemble-averaged amplitude, of light propagating through a scattering medium by use of a modified Shack-Hartmann procedure. This method avoids the difficult problem of phase unwrapping required in our previous method. We analyzed this process by first considering the basic Shack-Hartmann process and then considered the effects of a scattering media and the effects of an ensemble-averaging process. We showed that the ability of the method to measure the phase becomes significantly more difficult as the scattering medium becomes more severe, as indeed is to be expected. However, when the phase of the wave-front is measured, the reconstructed wave-front can be back projected to form a focused image of the absorbing objects embedded in the medium, thus obtaining resolution significantly better than is possible with the conventional first arriving light method. (References 3, 8, 14).

2. Our investigation of ensemble averaged imaging showed the importance of the spatial coherence function in imaging through scattering media, and also the importance of the coherence function in understanding the limitation of image formation through scattering media. We thus launched a research program into the spatial coherence relations that exist in the ensemble-averaged field from the scattering medium. We carried out an analysis of the coherence properties of light emerging from the medium. An extensive program in researching the coherence relations and their impact on the ability to image through scattering media was started. We believe that the best way to study image formation through scattering media is via the mutual coherence function. For example, the ballistic light leads to a broad mutual coherence function on the exiting surface of the scattering medium: furthermore, this light is coherent with the incident light and can be extracted from the background by interferometric methods, such as electronic holography. More interesting is the so-called snake light, the only light of concern in severely scattering media, where the ballistic light is absent. The snake light produces on the exiting surface a mutual coherence function that is typically narrow, of the order of a mm. If it is desired to obtain the phase of the exiting light, the mutual coherence function area determines the accuracy to which this can be done. From this viewpoint, the purpose of the first arriving light is to increase the area of this coherence function, thus permitting better resolution of objects hidden behind of within the medium. (Reference 16).

3. We considered the angular correlation that exists when two plane waves enter a scattering medium. The angular correlation was obtained from wave-front sensor data. One result of the research is the description of a technique for optical measurement of the complex angular correlation function of an arbitrary scattering medium over a continuous range of scattering angles. Previously this had been accomplished only for controlled media through the use of computer simulations. This technique should prove useful for both the theoretical aspects of angular correlation and in the recovery of object wave-fields from coherence measurements. Another result is the mathematical description of the output of a wave-front sensor for light of any degree of spatial coherence. Conventionally, wave-front sensors are applied to lightwaves that are assumed to be coherent; our results therefore extend the applicability of the device. (References 10,18,22).

4. The spectral fringe technique that we developed for capturing the first arriving light in photon migration processes was extended and generalized to include the reflection case (the basic photon migration first arriving light process is an inherently transmissive, not reflective, process). We have also investigated other examples of scattering and dispersive methods, including optical fibers, the contouring of surfaces, both specular and diffuse, and imaging through and into scattering media, using reflected instead of transmitted light. (References 12, 13, 15).

5. We explored a new concept we call generalized confocal imaging. We noted the similarity between confocal microscopy and synthetic aperture radar. We developed this similarity at length, leading to the concept of generalized confocal imaging. We developed the theory of generalized confocal imaging, in which there is the generalized process as a continuum, with synthetic aperture at one end of the continuum and confocal imaging at the other. We showed how the basic properties of one technique transform into corresponding properties of the other as we move across the continuum. We explored the properties of the intermediate region where these transformations take place. (Reference 17).

6. We extended our work on generalized confocal imaging by relating it to volume reflection holography, wherein a volume reflection hologram is made in spatially incoherent light. This work is a step further in our generalization of the confocal imaging process and its relation to holography. (Reference 26).

7. We developed a new idea that is useful for research into our continuing project of imaging through scattering media; this idea we expect will significantly facilitate our research. We can generate extremely short time gates using monochromatic light and a spatial filtering system. Thus, experiments for testing new ideas in imaging through scattering media can be accomplished with an order of magnitude reduction in the required equipment and in the required time. The method, we point out, cannot be of itself a technique for imaging into scattering media, but only one for testing techniques for imaging through scattering media. This limitation arises from the requirement that the scattering medium used in this technique must consist of discrete scatterers, such as a stack of thin scatter plates. This requirement precludes its use except as a test bed technique for evaluation of new ideas. However, within this limitation, the technique has enormous power. Of particular interest is how the imaging properties behave when the gate becomes extremely short, as will occur when an optical pulse of only a few femtoseconds is used, or equivalently, when a coherence gate of only a few femtoseconds is used.

   We used this method to study the imaging process through scattering media when the time gate becomes extremely short, of the order of a femtosecond. As the gating time becomes shorter, the ensemble-averaged light becomes increasingly coherent. Analysis shows, that with increasing coherence, an image-bearing wave propagating through the system produces a clearer, more diffraction-limited image, which is to say the effect of the scatter diminishes. However, the small aperture that produces the gating also acts like a limiting aperture, which degrades the resolution. As the gating aperture becomes smaller, there eventually is a crossover point, where the resolution loss due to smallness of the aperture (or apertures, since there is such an aperture in each unit of the system) equals the resolution loss due to scatter. Beyond this the resolution is then determined primarily by the aperture, with the scatter now becoming essentially irrelevant. Thus, the resolution becomes the diffraction-limited resolution of a high f-number system. Beyond this, shortening the gate leads to poorer resolution, not better.

The method has extreme flexibility and is easily carried out using only cw monochromatic light. Gating times far shorter than can be obtained by the usual pulsing or coherence methods can easily be produced; for example, gating times corresponding to less than a femtosecond can be explored. We expect this technique to be used in our future work on gating; the use will be as a test-bed to test the efficacy of new ideas in gating. (References 11, 16, 23, 24).

8. Phase conjugation methods.

In an earlier publication on phase conjugation we suggested an auxiliary technique of phase conjugation that we never pursued further, and we are not aware that anyone else has either. Initial experiments indicate that it can have application to this project. As was pointed out, the phase conjugation process can be extremely sensitive to any change in the optical properties of the inhomogeneous medium between the time of the first transit through the medium, and the propagation of the conjugate wave through the medium in the reconstruction process. If the medium has a complex structure, even the most minute changes in the transmission properties can very quickly degrade the reconstruction process. Thus, the phase conjugation process can be used to detect the most minute changes in these optical properties by measuring the degree of degradation of the reconstruction process.

We recently performed an experiment to test this possibility. Light from a point object was passed through a scattering medium and the emerging field was recorded as a hologram. The conjugate wave was produced and passed through the medium in a way so as to exactly duplicate the original object wave. When this is done carefully, the result is an image of the point, with excellent resolution and a high signal to noise ratio (SNR). SNR's of 40 db. Can be achieved, although the precise ratio that is attainable is rather flexible, since the ratio depends on how much of the scattered field is collected for the conjugation process. The process becomes less sensitive when the hologram or crystal mixer or other conjugator records only a portion of the scattered field, or if there are absorbing structures in the scattering medium, so that part of the field incident on the object is lost prior to the conjugation process. If now the scattering material is altered in some way, either by an external agent such as pressure or temperature changes, or due to some medium-occurring changes such as the growth or death of cells in biological tissue, the result will be manifested in a decreased SNR or a broadening of the reconstructed image point or both. This process appears to be a powerful and flexible method for measuring changes in the scattering media, i.e. for characterizing the time-change property of the medium. (Reference 21).

9. Vector field detection up-conversion method.

A new method of recording the scattered light using a short (40 fs) pulse produces a high contrast image of embedded objects. The method uses an up-conversion

technique in which the upconverted light, that which mixes with the reference beam in a non-linear crystal, is both spectrally and spatially separated from the background light. Most interestingly, the process does a vector mixing of the object and reference beams, so that only that component of the object beam with the propagation vector aligned approximately with the reference beam propagation vector gets up-converted to a higher frequency. This significantly alleviates the gating tolerances; indeed, in the preliminary experiments thus far carried out, the image quality was independent of the position of the gate, which now no longer had to be adjusted to capture the first arriving light. In more complex scattering media than was used in the experiment, this independence between gating time and image quality is only approximate, but it appears that the timing precision required of the gate is significantly reduced. (Reference 19).

C. List of papers submitted or published under ARO sponsorship on this grant:

1. P. Naulleau, D. Dilworth, E. Leith, and J. Lopez, "Resolution-enhanced detection of moving objects embedded within scattering media using time-gated speckle methods," Appl. Opt. **35**, 3065-3067, June 1996.

2. P. Naulleau, C. Chen, and E. Leith, "Analysis of direct three-dimensional image transmisson through optical fibers by the use of coherence methods," Appl. Opt. **35**, 3953-3962, July 1996.

3. E. Leith, P. Naulleau, and D. Dilworth, "Ensemble-averaged imaging through highly scattering media," Optics Letter **21**, 1691-1693, October 1996.

4. E. Arons, E. Leith, A.-C. Tien, and R. Wagner, "High-resolution optical chirped pulse gating," Appl. Opt. **36**, 2603-2608, April 1997.

5. E. Arons and D. Dilworth. "Improved imagery through scattering materials by quasi-Fourier-synthesis holography," Appl. Opt. **35**, 3104-3108, June 1996.

6. P. Naulleau and D. Dilworth, "Noise analysis for the holographic first-arriving-light technique," Appl. Opt. **35**, 3841-3852, July 1996.

7. P. Naulleau and D. Dilworth, "Motion-resolved imaging of moving objects embedded within scattering media by the use of time-gated speckle analysis," Appl. Opt. **35**, 5251-5257, September 1996.

8. P. Naulleau, E. Leith, H. Chen, B. Hoover, and J. Lopez, "Time-gated ensemble-averaged imaging through highly scattering media," Appl. Opt. **36**, 3889-3894, June 1997.

9. P. Naulleau, D. Dilworth, B. Hoover, J. Lopez, and E. Leith, "Holography under adverse conditions," Proc. Of International Conference on Display Holography, July 1997. Published by SPIE.

10. B. Hoover, "Optical determination of field angular correlation for transmission through three-dimensional turbid media," J. Opt. Soc. Am. **16**, 1046-1048 1999.

11. E. Leith, B. Hoover, S. Grannell, K. Mills, H. Chen, and D. Dilworth, "Realization of time gating by use of spatial filtering," Appl. Opt. **38**, 1-7, March 1999.

12. M. Shih, "Spectral holography for imaging through scattering media," Appl. Opt. **38**, 743-750, February 1999.

13. M. Shih, H. Chen, and E. Leith, "Spectral holography for coherence-gated imaging," Opt. Lett. **24**, 52-54, January 1999.

14. E. Leith, B. Hoover, D. Dilworth, and P. Naulleau, "Ensemble-averaged Shack-Hartmann wave-front sensing for imaging through turbid media," Appl. Opt. **37**, 3643-3650, June 1998.

15. I. Iglesias, H. Chen, K. Mills, D. Dilworth, and E. Leith, "Electronic channel fringe holography for depth and delay measurements," Appl. Opt. **38**, 1-9, April 1999.

16. E. Leith, "Coherence methods for unconventional imaging processes," presented at NATO technical conference in Jerusalem, Israel, October 1998 and published in the proceedings. INVITED PAPER.

17. E. Leith, K. Mills, P. Naulleau, D. Dilworth, I. Iglesias, and H. Chen, "Generalized confocal imaging and synthetic aperture imaging," J. Opt. Soc. Am. A/Vol. **16**, No. 12, December 1999.

18. B. Hoover, "Comparison of field correlations in multiply-scattered quasimonochromatic light," Appl. Opt. **39**, 3978-3983, August 2000.

19. A. Kuditcher, B. Hoover, M. Hehlen, E. Leith, S. Rand, and M. Shih, "Ultrafast, cross-correlated harmonic imaging through scattering media," Submitted to Appl. Opt.

20. G. Yang, H. Chen, and E. Leith, "Volume reflection holographic confocal imaging," Appl. Opt. **39**, 4076-4079, August 2000.

21. H. Chen and E. Leith, "Phase conjugation for change detection in scattering media," In Preparation.

22. B. Hoover, L. Deslauries, R. Ahmed, S. Grannell, D. Dilworth, B. Athey, and E. Leith, "Correlations among angular wave component amplitudes in elastic multiple-scattering random media," Submitted to Physics Review A.

23. K. Mills, B. Athey, L. Deslaurier, D. Dilworth, S. Grannell, B. Hoover, and E. Leith. " Investigation of ultrafast time gating by spatial filtering," Submitted to Applied Optics.

24. E. Leith, K. Mills, B. Athey, and D. Dilworth, "Analysis of time gated imagery through scattering media by Fourier optics," In Preparation.

In addition, various oral papers were presented at various conferences, including the Optical Society of America, the SPIE, and an ICO conference in Cancun, Mexico.

D. List of all participating scientific personnel:

1. Emmett Leith, PI
2. Marian Shih, Visiting Professor
3. Hsuan Chen, Visiting Professor
4. Brian Hoover, Graduate Student (PhD in 2000)
5. Kurt Mills, Graduate Student
6. Louis Deslaureirs, Graduate Student

E. Report of Inventions.

We made patentable inventions, but through publications they have gone into the public domain.

AUGMENTATION AWARDS FOR SCIENCE & ENGINEERING RESEARCH TRAINING (AASERT) REPORTING FORM

The Department of Defense (DoD) requires certain information to evaluate the effectiveness of the AASERT Program. By accepting this Grant which bestows the AASERT funds, the Grantee agrees to provide 1) a brief (not to exceed one page) narrative technical report of the research training activities of the AASERT-funded student(s) and 2) the information requested below. This information should be provided to the Government's technical point of contact by each annual anniversary of the AASERT award date.

1. Grantee identification data: (ARO Proposal Number and Grant numbers found on Page 1 of Grant)

a. University of Michigan
University Name

b. DAAG55-97-1-0243
Grant Number

c. P-36938-PH-AAS
ARO Proposal Number

d. Emmett N. Leith
P.I. Name

e. From: 6/1/97 To: 8/31/00
AASERT Reporting Period

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2. Total funding of the Parent Agreement and the number of full-time equivalent graduate students (FTEGS) supported by the Parent Agreement during the 12-month period prior to the AASERT award date.

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b. Number FTEGS: 1

3. Total funding of the Parent Agreement and the number of FTEGS supported by the Parent Agreement during the current 12-month reporting period.

a. Funding: $ 60,000

b. Number FTEGS: 1

4. Total AASERT funding and the number of FTEGS and undergraduate students (UGS) supported by AASERT funds during the current 12-month reporting period.

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b. Number FTEGS: 1

c. Number UGS: 0

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Emmett N Leith
Principal Investigator

JAN 15 2001
Date